UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

# eRD18 - Precision Central Silicon Tracking & Vertexing for the EIC

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* Postdoctoral researcher
** PhD student

# eRD18: Proposal

To develop a detailed concept for a central silicon vertex detector for a future EIC experiment, exploring the potential advantages of depleted MAPS (DMAPS) technologies

**Physics motivation**

Open heavy flavour decays – **high position resolution**

Precision tracking of high $Q^2$ scattered electrons – **low mass**

**WP1: Sensor Development**

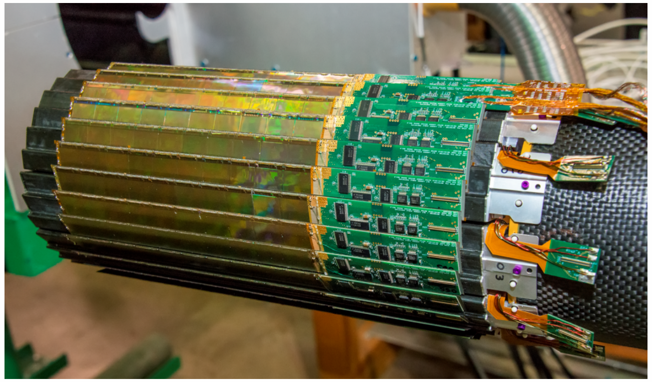
Exploit on-going R&D in Birmingham into DMAPS to investigate potential solutions for the EIC

**WP2: Silicon Detector Layout Investigations**

Optimise the numbers of layers, layout and spatial resolution to achieve the required tracking and vertex reconstruction performance

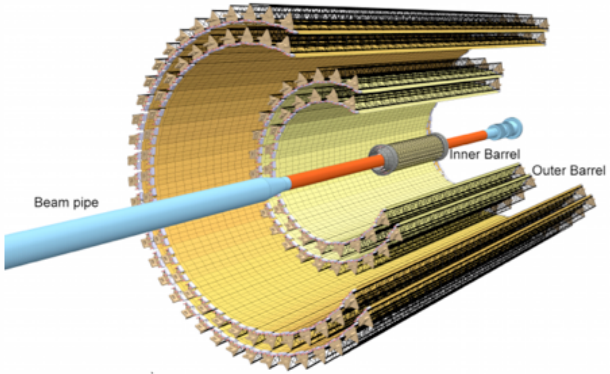
# Background: State-of-the-art MAPS

**STAR** Heavy Flavour Tracker (HFT) at RHIC



MIMOSA (AMS 0.35 μm CMOS process)

**ALICE** Inner Tracking System (ITS) Upgrade at LHC

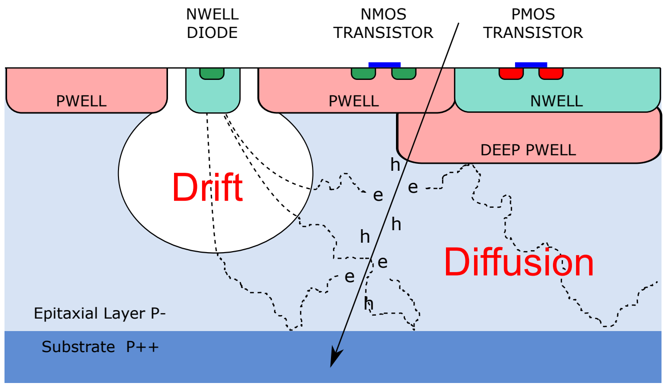



ALPIDE (TowerJazz 0.18 μm CMOS process)

- Key features of MAPS
  - Small pixel size (down to 20 μm x 20 μm)
  - Low power (< few hundred $mW/cm^2$)
  - Low material budget (~ 0.3% $X_0$ per layer)
  - Moderate radiation hardness (~Mrad, $10^{13}$ 1MeV $n_{eq}/cm^2$)

# Background: State-of-the-art MAPS

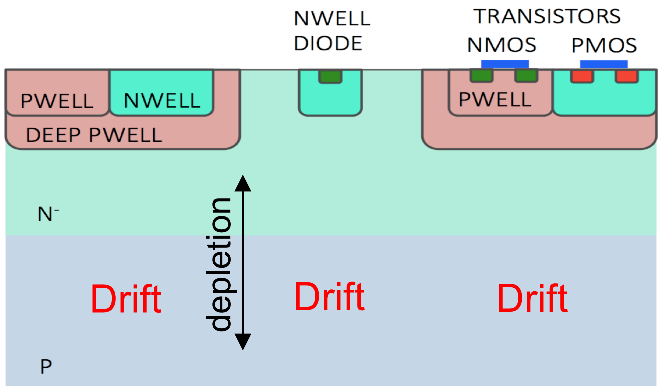
- Starting point is the ALICE ALPIDE sensor (MAPS)




**ALPIDE sensor**

- 0.18 μm CMOS *standard* TowerJazz (TJ) process
- 28 x 28 $\mu m^2$ pixel pitch
- Small collection electrode = low capacitance
- Partially depleted; charge collection *in part* by drift

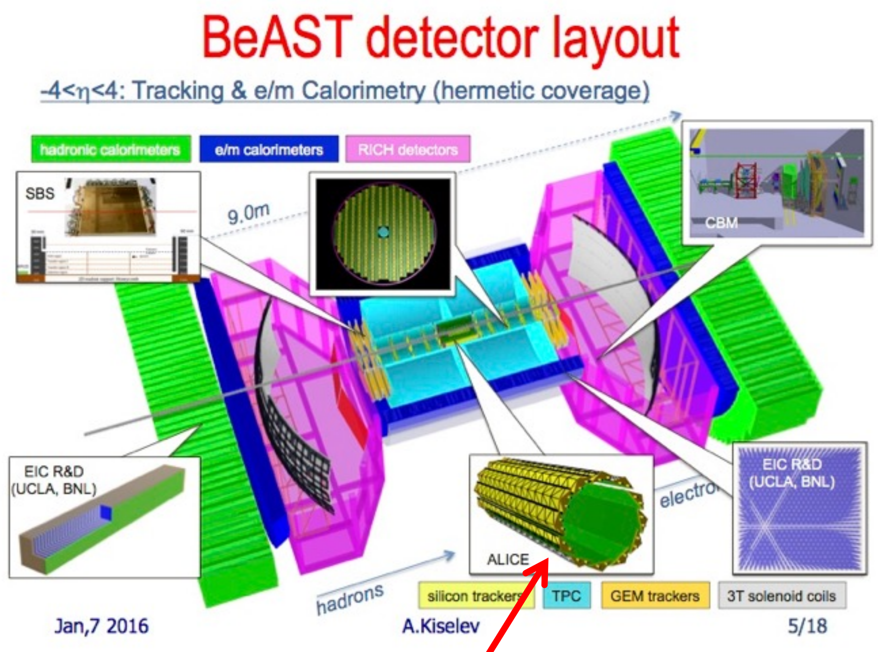
- Future is fully depleted MAPS (DMAPS)



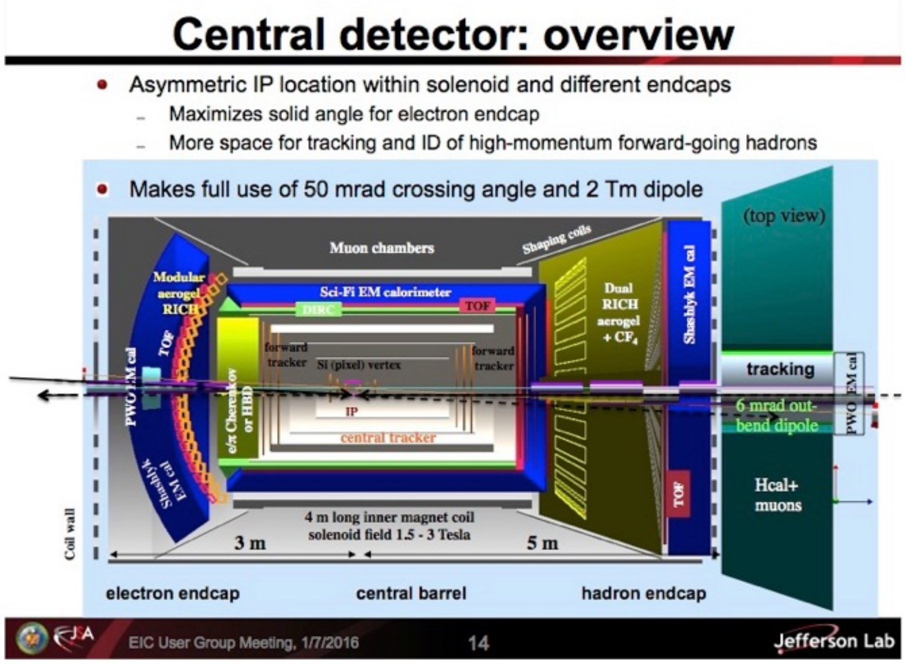

**Example: TowerJazz modified process**

- 0.18 μm CMOS *modified* TowerJazz (TJ) process
- Introduces additional planar junction
- Fully depleted sensor; charge collection by drift
- Faster, more complete charge collection
- Less charge sharing between pixels

# Background: EIC Detector Concepts




Alexander Kiselev




Pawel Nadel-Turonski

Based on **ALICE ITS** inner layer design

- Si vertex and tracker detectors in central and forward regions
- Seek high resolution, high s/n, low mass, low power solution
  - applicable to both eRHIC and JLEIC

# WP1: Sensor development

- Aim: to demonstrate *high spatial resolution* in a *fully depleted* sensor
  - Advantage of depletion = charge collection by drift
    - ➔ larger Q, faster collection, smaller cluster multiplicity
    - ➔ plus improved radiation hardness (not essential for the EIC)

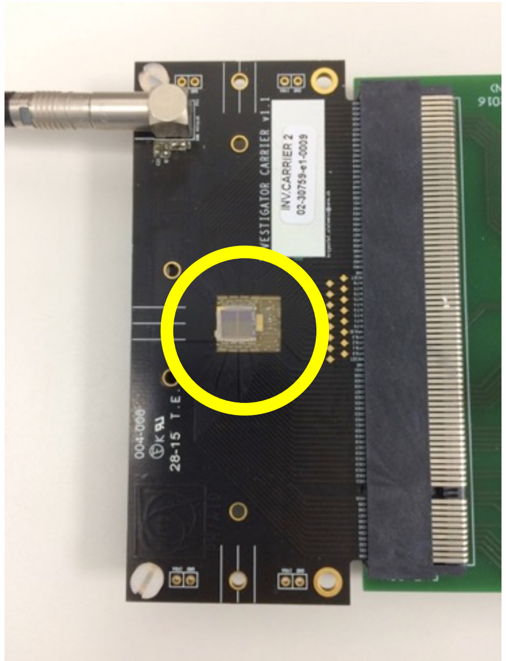
- Technology development
  - Exploiting our involvement in other projects (not EIC specific)

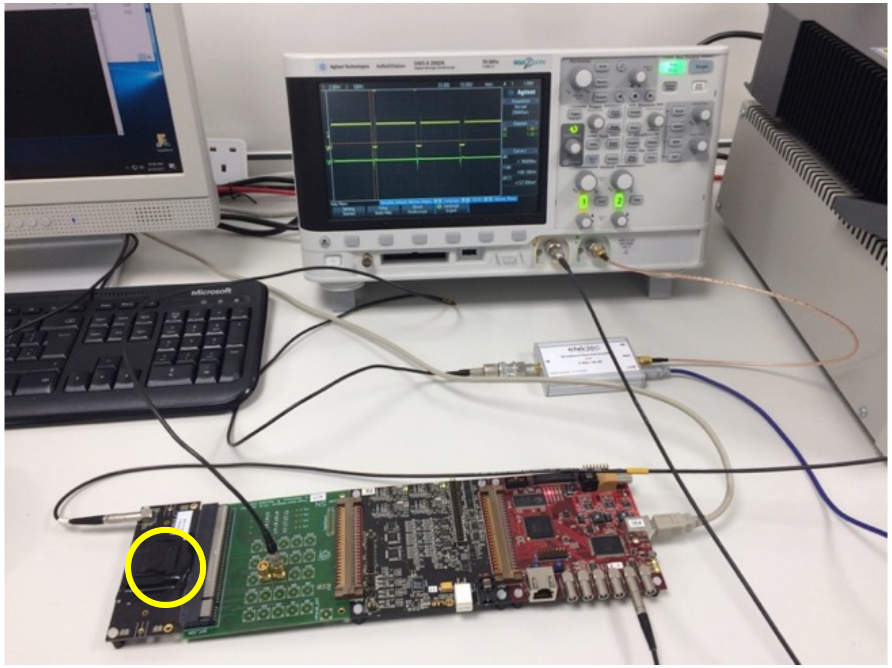
| Project | Pixel sizes | Electrode | Process | Availability |
|---|---|---|---|---|
| CERN-TJ | 20 x 20 $\mu m^2$ to 50 x 50 $\mu m^2$ | Single small | TJ standard<br>TJ modified | Now |
| DECAL | 50 x 50 $\mu m^2$ | Multiple | TJ standard<br>TJ modified | Now<br>Spring |
| RD50 | ≥ 20 x 20 $\mu m^2$ | Single large | LFoundry | 2019 |

  - Current focus is the CERN-TJ investigator chip
  - Permits a comparison between *standard* and *modified* processes

# WP1: Sensor development

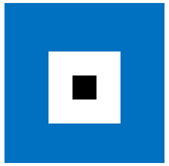
- CERN-TJ investigator chip now available for testing in Birmingham
  - Designed to study charge collection properties and detection efficiency
  - More than 100 pixel matrices (8 x 8 pixels)
  - Range of pixel sizes relevant to both EIC barrel and disks
    - 20 x 20 $\mu m^2$ to 50 x 50 $\mu m^2$ pixels
  - Simple follower-based (analogue-only) readout



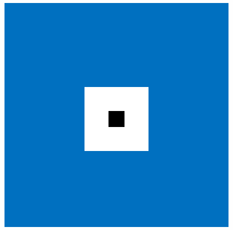


# WP1: Sensor development

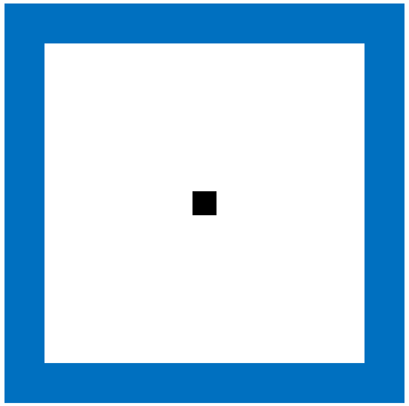
- CERN-TJ Investigator: first look



Pixel: 20 x 20 $\mu m^2$
Electrode: 3 x 3 $\mu m^2$
Electrode spacing: 3 $\mu m$



Pixel: 28 x 28 $\mu m^2$
Electrode: 2 x 2 $\mu m^2$
Electrode spacing: 3 $\mu m$ ✓



Pixel: 50 x 50 $\mu m^2$
Electrode: 3 x 3 $\mu m^2$
Electrode spacing: 18.5 $\mu m$

Available pixel matrices

| | |
|---|---|
| 0-35: | 20 x 20 $\mu m^2$ |
| 36-57: | 22 x 22 $\mu m^2$ |
| 58-67: | 25 x 25 $\mu m^2$ |
| 68-103: | 28 x 28 $\mu m^2$ |
| 104-111: | 30 x 30 $\mu m^2$ |
| 112-123: | 40 x 40 $\mu m^2$ |
| 124-133: | 50 x 50 $\mu m^2$ |

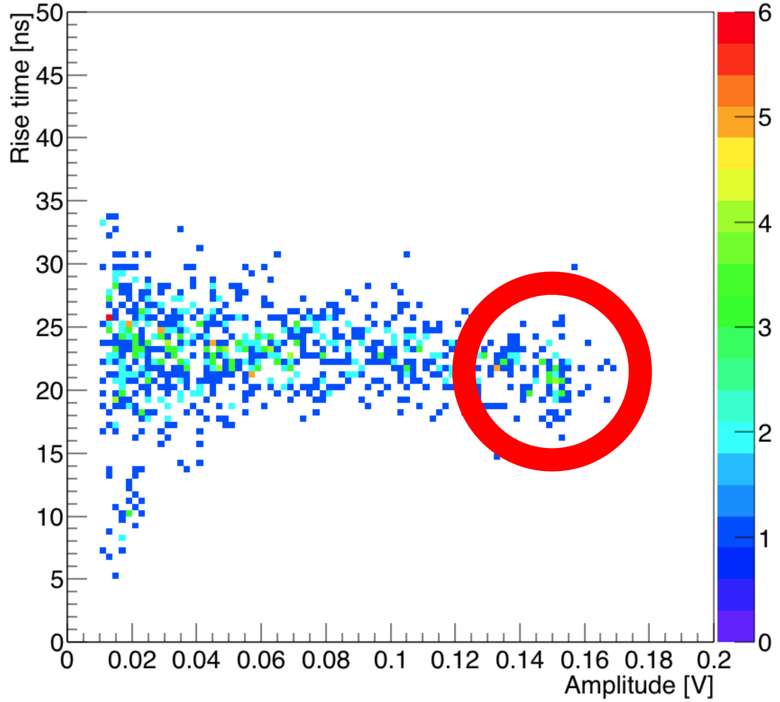
Electrode sizes
1-5 $\mu m^2$

Electrode spacing
1-5 $\mu m$ typically
(except 50 x 50 $\mu m^2$ pixels)

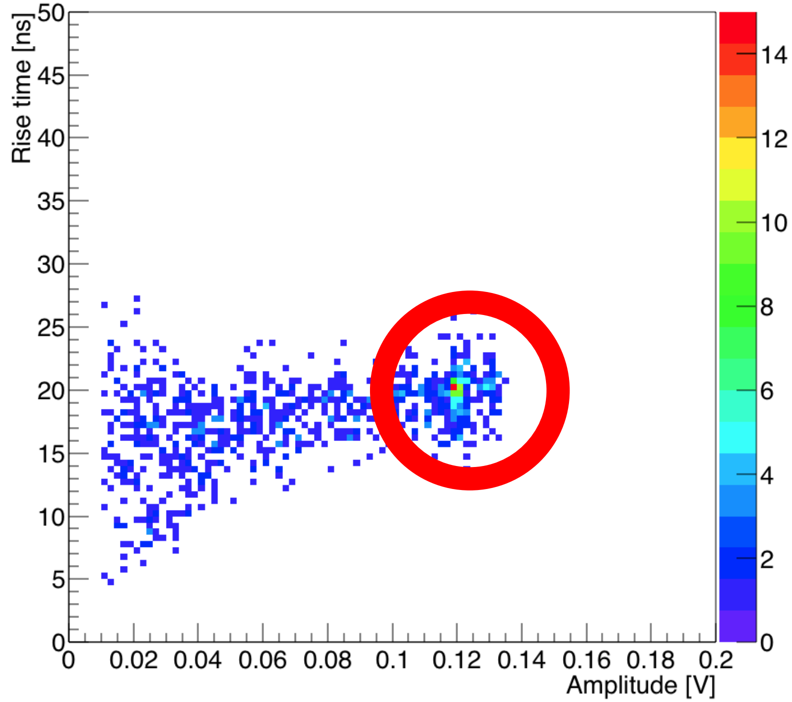
# WP1: Sensor development

- Comparison of TJ *standard* and *modified* processes
  - 28 x 28 μm$^2$ pixels, tests with $^{55}$Fe source

Standard TJ process



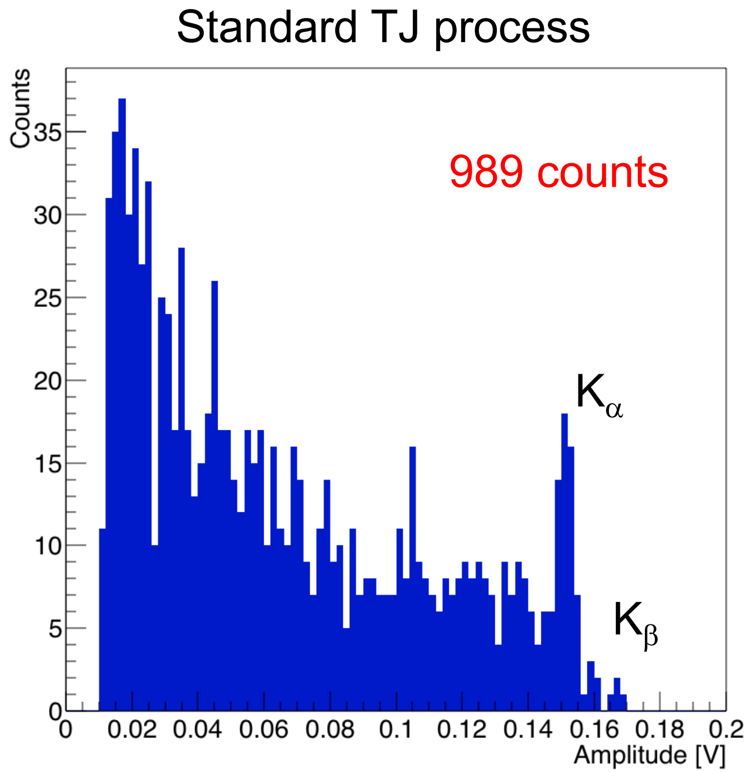

Modified TJ process

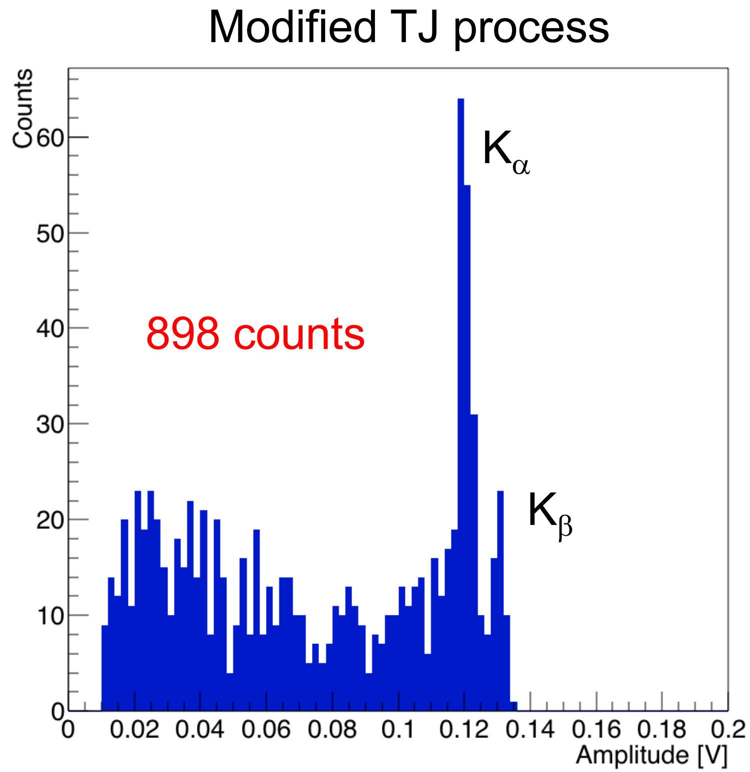



  - More large amplitude signals with the modified process
    - Due to more complete charge collection

# WP1: Sensor development

- Comparison of TJ *standard* and *modified* processes
  - 28 x 28 $\mu m^2$ pixels, tests with $^{55}Fe$ source

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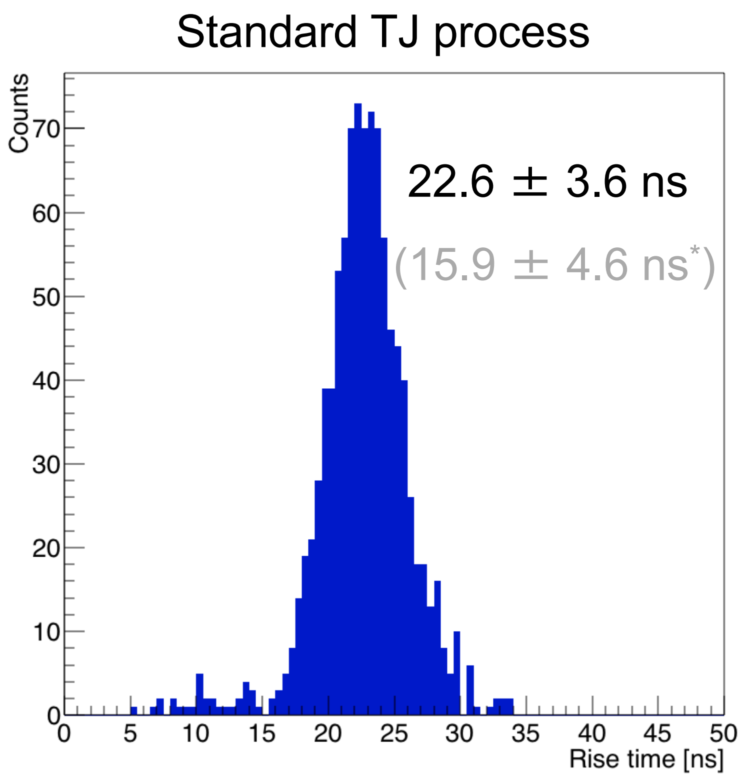
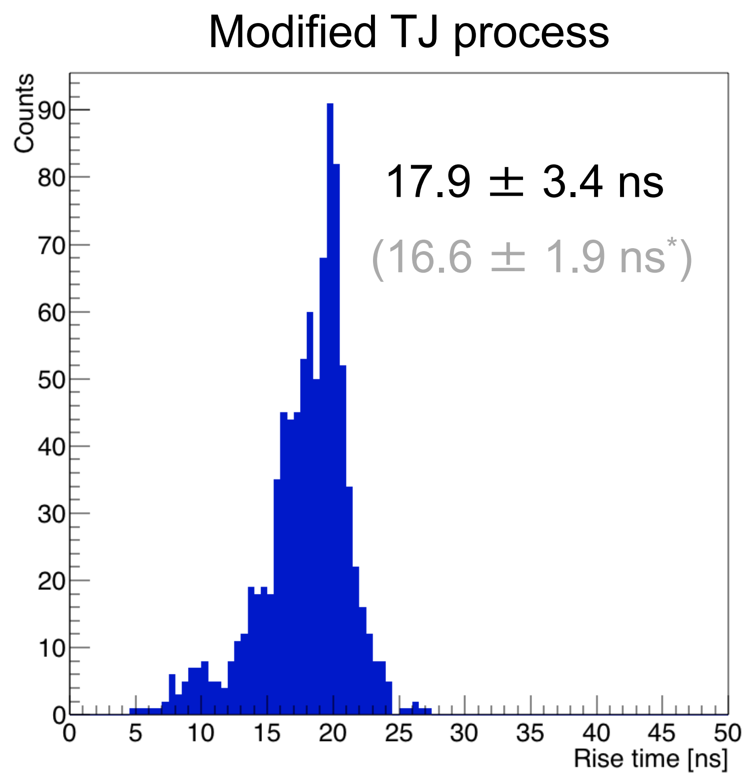
  - 28 x 28 $\mu m^2$ pixels, tests with $^{55}Fe$ source




  - Modest improvement in signal rise time for the modified process
  - Note: published studies* ~ 16 ns (50 x 50 $\mu m^2$ pixels)

* H. Pernegger et al., 2017 JINST 12 P06008

# WP1: Sensor development

- Update on other developments
  1. DECAL prototype in TowerJazz standard process
     - Part of a separate Digital ECal (DECAL) project (UK funded PRD)
     - Consists of larger pixels (50 x 50 $\mu m^2$) and four small collection electrodes to match requirements of DECAL project
     - Undergoing initial tests; readout being developed
  2. DECAL test structures in TowerJazz modified process
     - Multi-Project Wafer submission with CERN in July
     - Consists of passive versions of the DECAL prototype pixels
  3. RD50 LFoundry submission expected by end of 2018
     - Matrices with **improved time resolution** (in-pixel TOA and TDC)
     - Test structures with pixels down to 20 x 20 $\mu m^2$
     - But, large electrode (electronics sits within the collecting n-well)

All options are useful for evaluation purposes …

Expect larger Q, but also larger C than single small electrode

# WP2: Simulations

- Update on manpower
  - EIC (FY17) R&D funds supported a postdoc for 5.5 months
  - Post filled by Dr. Sam Bailey; left to take up a new job in the summer
  - A new UoB-funded PhD student (Håkan Wennlöf) started in October
  - Håkan performed all the initial tests of the CERN-TJ investigator
  - He has now started to revisit the simulations work started by Sam
- Focus on simulations in EicRoot software framework
  - Studied pions (kaons and protons) from 500 MeV/c to 10 GeV/c
  - Various barrel configurations plus default TPC specification
    - 4-layer barrel, default geometry, 20-40 $\mu$m pixels
    - 3, 4 and 5-layer barrels, 30 $\mu$m pixels
- Plan for the next 6 months
  - Optimise the number and radial position of the layers
  - Mainly concerned with pointing resolution at low $p_T$
  - Consider option of having an outermost layer with lower intrinsic resolution (larger pixels) but added timing capability

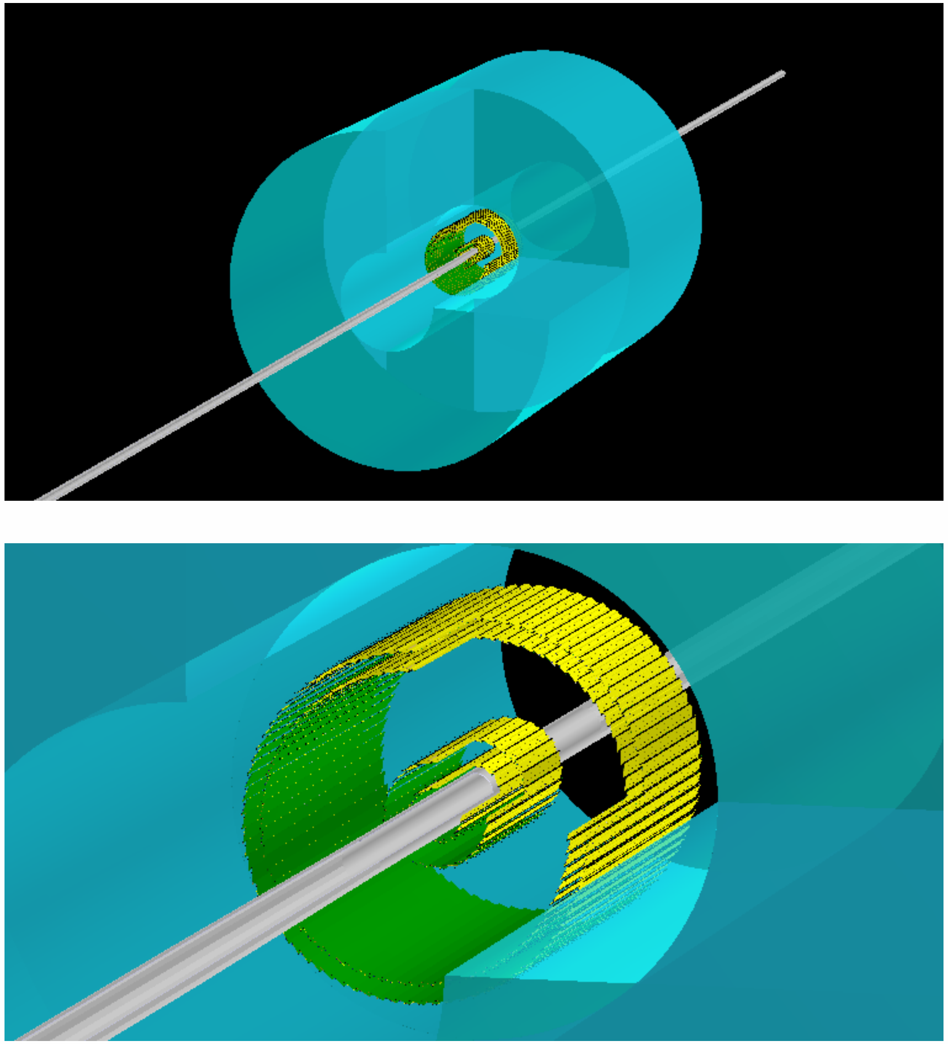
# eRD18: Project summary

- WP1: Sensor development
  - Started characterisation of CERN-TJ investigator
  - Demonstrated improved charge collection with the modified process
  - Currently investigating amplifier behaviour with vendor (CIVIDEC) to understand the dependence of rise time on signal amplitude
  - Plan to continue characterisation studies with a new amplifier
- WP2: Simulations
  - Restarting simulation studies
  - Optimise the number and radial position of the layers
  - Aim for pointing resolution ~ 30 $\mu$m at 1 GeV/c (cf. $D^0$ $c\tau \approx 120$ $\mu$m)
  - Consider option of a tracking layer with added timing capability
    - Outer layer with larger pixels
    - Optimise pixel size with outer tracker
    - Consult with a chip designer to estimate power requirement

# Backup Slides

# WP2: Simulations

- Geometry: TPC + VST + beam pipe + magnetic field (B = 1.5 T)



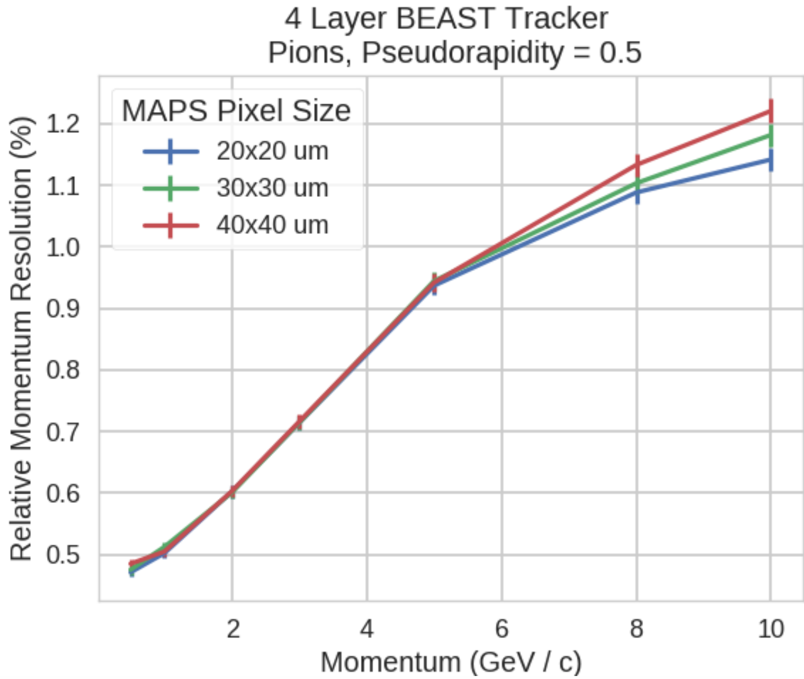
TPC parameters
Inner radius = 20 cm
Outer radius = 80 cm
250 μm position resolution

VST parameters
Layer #1 radius = 2.3 cm
Layer #2 radius = 4.6 cm
Layer #3 radius = 14 cm
Layer #5 radius = 16 cm
30 x 30 μm pixels
0.3% $X_0$ per layer

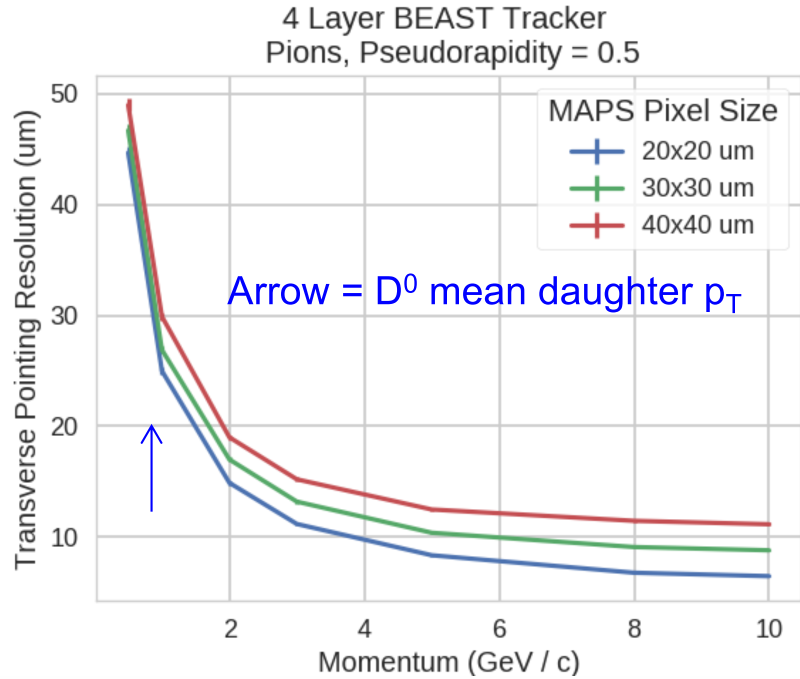
Beam pipe parameters
Material = beryllium
Outer radius = 1.8 cm
Thickness = 0.8 mm

# WP2: Simulations

- Results: pions; eta = 0.5; 3 pixel sizes: 20 μm, 30 μm and 40 μm




Relative momentum resolution (%)
versus momentum

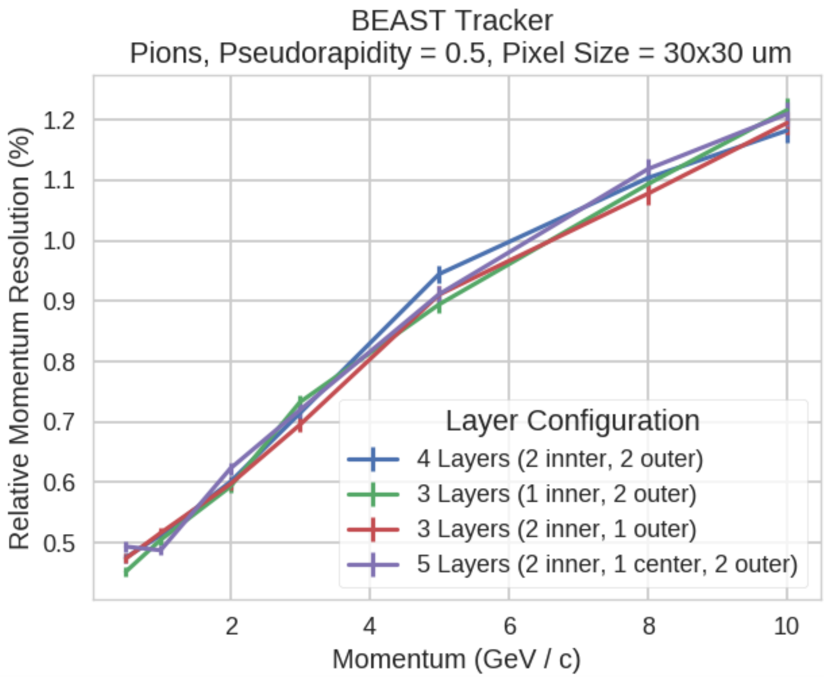



Impact parameter resolution (μm)
in transverse (r-ϕ) plane
versus momentum

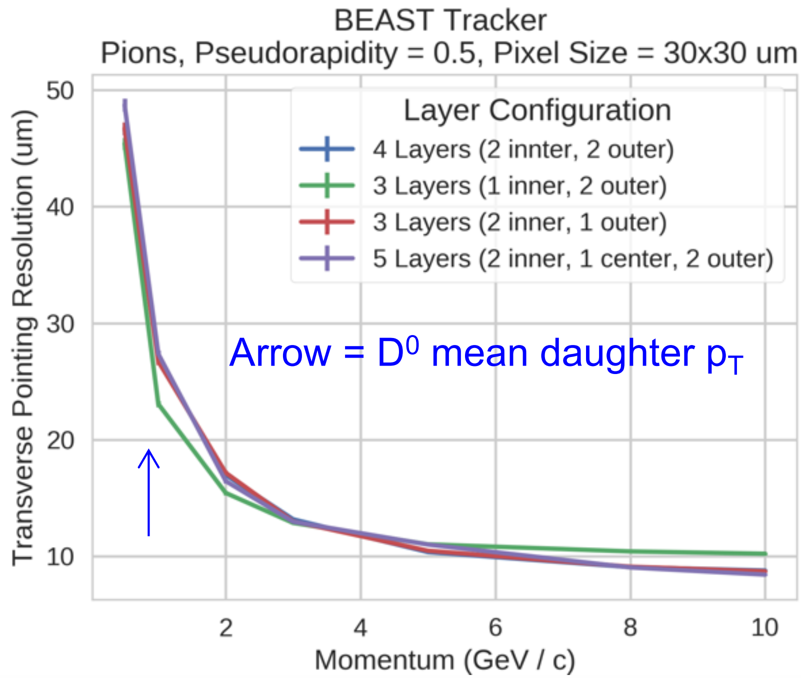
- Modest improvement in impact parameter resolution for all $p_T$
  - Dominated by resolution of innermost layer

# WP2: Simulations

- Results: pions; eta = 0.5; pixel size = 30 $\mu$m; 3, 4 and 5 layers



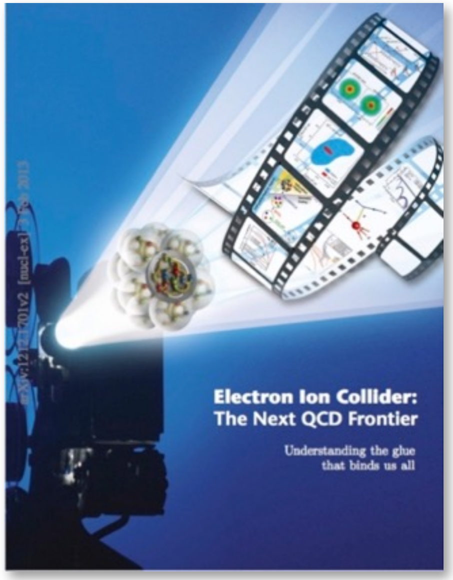

Relative momentum resolution (%)
versus momentum




Impact parameter resolution ($\mu$m)
in transverse (r-$\phi$) plane
versus momentum

- Little sensitivity to the number of layers
  - Slightly better impact parameter resolution with one inner layer

# Charm observables in the EIC White Paper



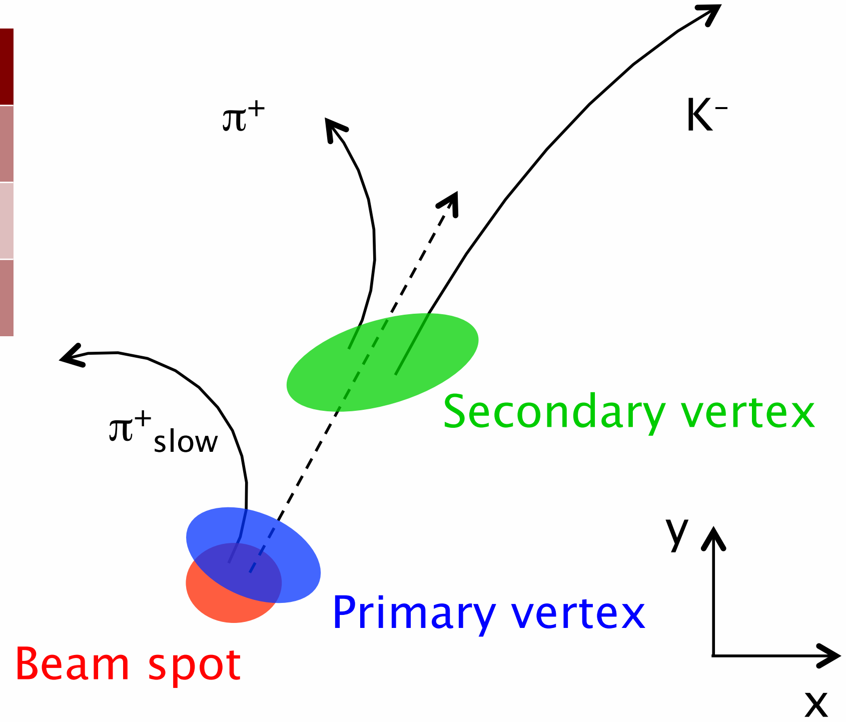

A. Accardi et al.,
Eur. Phys. J. A (2016) 52:268

- Leading order charm production process is $\gamma$g fusion
- Provides sensitivity to:
  I. The gluon contribution to spin of the nucleon
     - Charm sensitive to $\Delta$g in e-p scattering
  II. Physics of high gluon densities and low-x in nuclei
     - Measurement of $F_2^{charm}$ sensitive to nuclear gluon density in e-A
  III. Hadronisation and energy loss in cold nuclear matter
     - Nuclear modification and quark mass dependence
- A future EIC promises unprecedented precision in charm (and beauty)
  – Reconstruction challenging due to short decay lengths ~ 100 $\mu$m
  – Likely to place strongest constraints on the tracker design
  – Potential importance of low-$p_T$ (standalone) tracking

# Open charm reconstruction

- Signature is displaced (secondary) decay vertex

| Particle | Decay | Branching | $c\tau$ [$\mu$m] |
|---|---|---|---|
| $D^0$ | $K^-\pi^+$ | 3.9% | 123 |
| $D^+$ | $K^-\pi^+\pi^+$ | 9.5% | 311 |
| $D^{*+}$ | $D^0\pi^+_{slow}$ | 67.7% | |




Example:

$$D^{*+} \rightarrow D^0\pi^+_{slow} \rightarrow \left(K^-\pi^+\right)\pi^+_{slow}$$

- Requires excellent impact parameter resolution in $r$-$\phi$ and $z$
  - Dominated by position and resolution of innermost tracking layer
    - Close as possible to beam pipe (caution: radiation environment)
    - Highest possible spatial resolution (small pixels)